DESIGN ANALYSIS AND IMPLEMENTATION OF SPACE VECTOR PULSE WIDTH MODULATING INVERTER USING DSP CONTROLLER FOR VECTOR CONTROLLED DRIVES

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ABSTRACT

The space vector PWM (SVPWM) algorithm is implemented using DSP controller to control the three-phase induction machines. SVPWM algorithm used in the experiment is simulated and the results are confirmed experimentally. Here, DSP processor computes the Voltage Space Vector and its components in (d, q) frame such as Vd, Vq, Vref, and angle (α).Also, it determines the switching time duration at any sector such as T1, T2, T0 and hence decides the switching time of each transistor (S1 to S6).SVPWM software parameters are observed and compared with the simulated ones. Also, the experimental outputs confirm the theoretical and simulation outputs. The different simulation and experimental results are observed and the analysis of the different results are presented.

Keywords: Space vector PWM**,** vector sectors, switching patterns

I. INTRODUCTION

Power conversion and control are performed by power electronic converters that are built by network of semiconductor power switches. The basic state of a voltage source converter can be distinguished by the operating states. To obtain a precise, quantitative definition of the dependent quantities, some means of formally and quantitatively describing switching pattern is to be identified

as an existence function (1). This mathematical expression allows dependent quantity and internal converter waveform to be constructed graphically. The existence function for a single switch assumes unit value whenever the switch is closed and is zero whenever the switch is open. In a converter, each switch is closed and opened according to some repetitive pattern. The simplest, or unmodulated, existence functions have pulses all of the same time duration and zero intervals with the same property (2). The more complex variety, which has differing duration of pulses and various interspersed zero times, is called a Modulated existence function. . In the conversion process, the defined quantities may be either current or voltage. This paper focuses on design and simulation of space vector pulse width modulated inverters (SVPWM).The model of a three-phase voltage source inverter is discussed based on space vector theory. The first part of the paper includes the mathematical modeling of the SVPWM for vector controlled drives. The second part describes the simulink model and the simulation results which are shown for different parameters. Simulation results are obtained using MATLAB/Simulink environment for effectiveness of the study. The SVPWM algorithm is implemented using DSP controller. The different simulation and experimental results are observed and the analysis of the different results are presented.

II. SPACE VECTOR PWM INVERTER

Three phase voltage-fed PWM inverters are recently showing growing popularity for multi-megawatt industrial drive applications. The main reasons for this popularity are easy sharing of large voltage between the series devices and the improvement of the harmonic quality at the output as compared to a two level inverter (2).The Space Vector Pulse Width Modulation of a three level inverter provides the additional advantage of superior harmonic quality and larger under-modulation range that extends the modulation factor to 90.7% from the traditional value of 78.5% in Sinusoidal Pulse Width Modulation.

The most widely used PWM schemes for three-phase voltage source inverters are carrier-based sinusoidal PWM and space vector PWM (SVPWM) (3). There is an increasing trend of using SVPWM because of their easier digital realization and better dc bus utilization. The parameters such as current harmonics, harmonic spectrum, torque harmonics, switching frequency, dynamic performance and polarity consistency rule decides the performance criteria of Space Vector PWM algorithms .In this paper, we have implemented SVPWM algorithm and proved its high performance with respect to other techniques.

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector **V** rotating in the counter clockwise direction as shown in Fig.1. The magnitude of this vector is related to the instantaneous magnitude of the output voltage and the period this vector takes to complete one revolution is the same as the fundamental time period of the output voltage. It is possible to express each phase-to-neutral voltage for every switching combination of IGBTs as listed in Table 1.
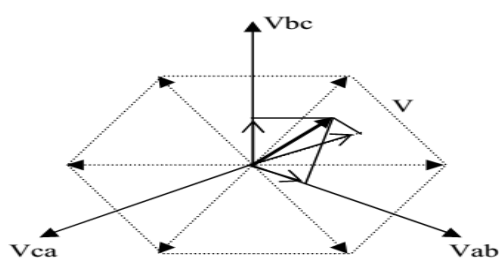

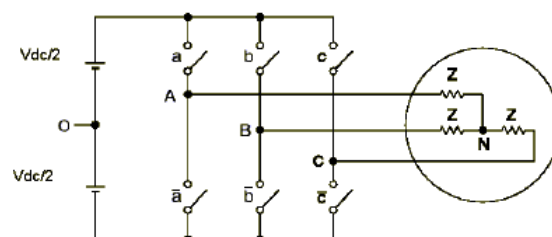**Fig 1** Output voltage vector (V) in (α -β) plane   **Fig. 2** Power Bridge

In vector control algorithm, the control variables are expressed in rotating frame .The current vector Is* that directly controls the torque is transformed into voltage vector by the inverse park transform.   This voltage reference is expressed in the (α-β) frame. Using this transformation, three-phase voltages (VAN, VBN, VCN) and the reference voltage vector are projected in the (α-β) frame. The expression of the three-phase voltages in the (α-β) frame are given by general Clarke transformation equation:

$$\begin{bmatrix} Vs\alpha \\ Vs\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{AN} \\ V_{BN} \end{bmatrix} \tag{1}$$

Table.1 POWER bridge output voltages

A	B	C	VAN	VBN	VCN
0	0	0	0	0	0
0	0	1	-Vdc/3	-Vdc/3	2Vdc/3
0	1	0	-Vdc/3	2Vdc/3	-Vdc/3
0	1	1	2Vdc/3	Vdc/3	Vdc/3
1	0	0	2Vdc/3	-Vdc/3	-Vdc/3
1	0	1	Vdc/3	2Vdc/3	Vdc/3
1	1	0	Vdc/3	Vdc/3	2Vdc/3
1	1	1	0	0	0

Table 2 Stator-Voltages in (α-β) frame and related voltage vector

A	B	C	Vα	Vβ	Vectors
0	0	0	0	0	V0
0	0	1	-Vdc/3	-Vdc/√3	V1
0	1	0	-Vdc/3	Vdc/√3	V2
0	1	1	-2Vdc/3	0	V3
1	0	0	2Vdc/3	0	V4
1	0	1	Vdc/3	-Vdc/√3	V5
1	1	0	Vdc/3	Vdc/√3	V6
1	1	1	0	0	V7

Since, only eight combinations are possible for the power switches,Vsα ,Vsβ,can also take finite number of values in the (α-β) frame(Table 4.2) according to IGBT command signals (a,b,c).The eight voltage vectors re-defined by the combination of the switches are represented in Fig. 3 Now, given a reference voltage (coming from the inverse park transform), the following step is used to approximate this reference voltage by the above defined eight vectors (4). In Figure 4, the reference voltage Vs* is the third sector and the application time of each adjacent vector is given by:
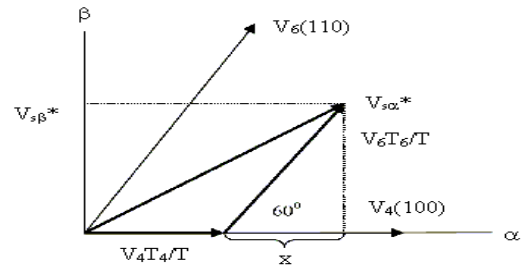
$$T = T_4 + T_6 + T_0 \quad \text{and} \quad V_S^* = T_4 V_4 / T + T_6 V_6 / T \tag{2}$$

The determination of the amount of times T4 and T6 is given by simple projections:

$$V_{S\beta}^* = T_6 |V_6| \cos(30) / T, \quad V_{s\alpha}^* = T_4 |V_4| / T + X, \quad X = V_{S\beta}^* / tg(60) \tag{3}$$

Fig.3 Voltage vectors

Fig. 4 Projection of the reference Voltage Vector

Finally, with the (α-β) component values of the vectors given in the Table 2, the amount of times of application of each adjacent vector is:

$$T4 = T\,(3V_{s\alpha}* - \sqrt{3}V_{s\beta}*)\,/\,2Vdc, \qquad T_6 = \sqrt{3}\,T\,V_{s\beta}*\,/Vdc \qquad (4)$$

The rest of the period spent in applying the null-vector. For every sector, commutation duration is calculated. The amount of times of vector application can all be related to the following variables:

$$X = \sqrt{3}\,V_{s\beta}*, \qquad Y = \sqrt{3/2}\,V_{s\beta}* + 3/2*V_{s\alpha}* \quad \text{and} \quad Z = \sqrt{3/2}\,V_{s\beta}* - 3/2\,V_{s\alpha}* \qquad (5)$$

In the previous example for sector 3, T4 = -Z and T6 = X. Extending this logic, one can easily calculate the sector number belonging to the related reference voltage vector. The following basic algorithm helps to determine the sector systematically.

If X > 0 then A=1   else A=0,   If Y > 0 then B=1   else B=0
If Z > 0 then C=1   else C=0,   Sector = A+2B+4C   (6)

Application durations of the sector boundary vectors are tabulated as;

Sector: (i)   t1= Z , t2= Y ,   (ii) t1= Y ,t2=-X   (iii) t1=-Z , t2= X
                  (iv)   t1=-X ,t2= Z   (v) t1= X , t2=-Y   (vi) t1=-Y , t2=-Z   (7)

Saturations:
 If (t1+ t2) > PWMPRD then   t1sat = (t1/ t1+t2)*PWMPRD and   t2sat = (t2/ t1+t2)*PWMPRD
The third step is to compute the three necessary duty cycles as;

$$t_{aon} = (PWMPRD - t1 - t2)\,/2, \qquad t_{bon} = t_{aon} + t1 \quad \text{and} \quad t_{con} = t_{bon} + t2 \qquad (8)$$
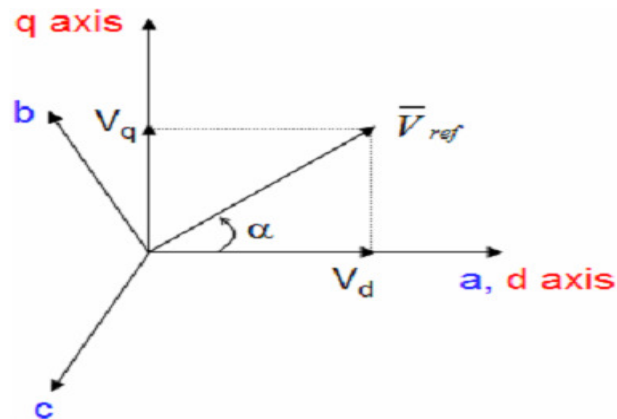
The last step is to assign the right duty cycle (txon) to the right motor phase (in other words, to the right (CMPRx) according to the sector.

Table 3 depicts this determination

	1	2	3	4	5	6
CMPR1	t_{bon}	t_{aon}	t_{aon}	t_{con}	t_{bon}	t_{con}
CMPR2	t_{aon}	t_{con}	t_{bon}	t_{bon}	t_{con}	t_{aon}
CMPR3	t_{con}	t_{bon}	t_{con}	t_{aon}	t_{aon}	t_{bon}

Fig. 5. Sector 3 PWM Patterns and Duty Cycles

Fig. 6. Voltage Space Vector and its components in (d, q).

III. SIMULATION of SVPWM INVERTERS

The space vector PWM algorithm can be implemented by the following steps:
Step 1. Determine Vd, Vq, Vref, and angle (α)
Step 2. Determine time duration T1, T2, T0
Step 3. Determine the switching time of each transistor (S1 to S6)

(i)   Step 1: Determine Vd, Vq, Vref, and angle (α)

Fig. 6. shows the Voltage Space Vector and its components in (d, q) .From Fig.6, the Vd, Vq, Vref, and angle (α) can be determined as follows:

$$V_d = V_{an} - V_{bn} \cdot \cos 60 - V_{cn} \cdot \cos 60$$

$$= V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn}$$

$$V_q = 0 + V_{bn} \cdot \cos 30 - V_{cn} \cdot \cos 30$$

$$= V_{an} + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn}$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

(9)

$$\therefore \left| \overline{V}_{ref} \right| = \sqrt{V_d{}^2 + V_q{}^2}$$

$$\therefore \alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega t = 2\pi f t, \quad \text{where } f = \text{fundamental frequency}$$

Step 2: Determine time duration T1, T2, T0

Figure 7 shows reference vector as a combination of adjacent vectors at sector From Fig. 7, the switching time duration can be calculated as follows:
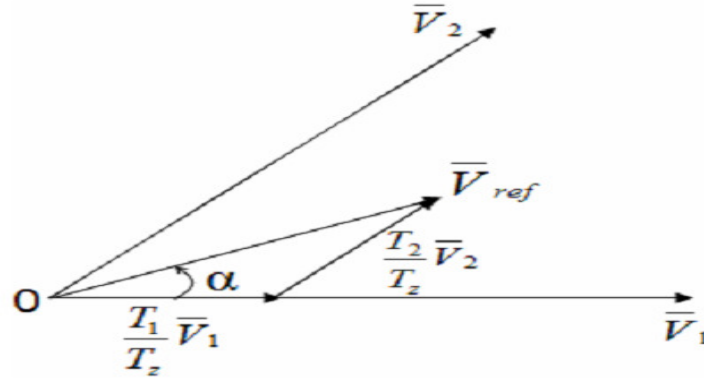
Switching time duration at Sector 1:

$$\int_0^{T_z} \overline{V}_{ref} = \int_0^{T_1} \overline{V}_1 dt + \int_{T_1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_z} \overline{V}_0$$

$$\therefore T_z \cdot \overline{V}_{ref} = (T_1 \cdot \overline{V}_1 + T_2 \cdot \overline{V}_2)$$

$$\Rightarrow T_z \cdot \left| \overline{V}_{ref} \right| \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

(where, $0 \le \alpha \le 60°$)

$$\therefore T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

$$\therefore T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

(10)

$$\therefore T_0 = T_z - (T_1 + T_2), \quad \left(\text{where, } T_z = \frac{1}{f_z} \text{ and } a = \frac{\left| \overline{V}_{ref} \right|}{\frac{2}{3}V_{dc}} \right)$$
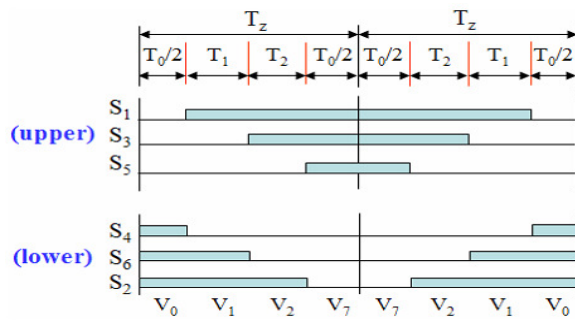
(11)

Switching time duration at any Sector:

$$\therefore T_1 = \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}} \left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right) \right)$$

$$= \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}} \left(\sin\frac{n}{3}\pi - \alpha \right)$$

$$= \frac{\sqrt{3} \cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}} \left(\sin\frac{n}{3}\pi\cos\alpha - \cos\frac{n}{3}\pi\sin\alpha \right)$$
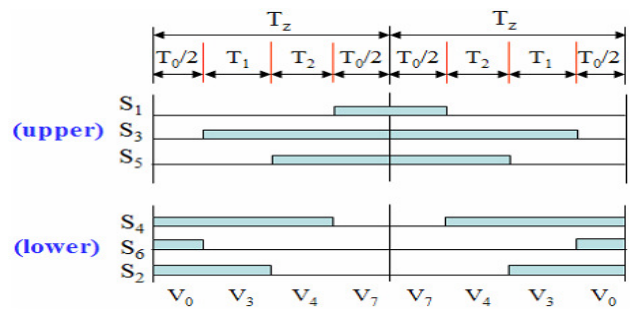
$$\therefore T_2 = \frac{\sqrt{3} \cdot T_z \cdot |\overline{V}ref|}{V_{dc}} \left(\sin\left(\alpha - \frac{n-1}{3}\pi \right) \right)$$

$$= \frac{\sqrt{3} \cdot T_z |\overline{V}ref|}{V_{dc}} \left(-\cos\alpha \cdot \sin\frac{n-1}{3}\pi + \sin\alpha \cdot \cos\frac{n-1}{3}\pi \right)$$

$$\therefore T_0 = T_z - T_1 - T_2, \quad \left(\begin{array}{l} \text{where, } n = 1 \text{ through } 6 \text{ (that is, Sector 1 to 6)} \\ 0 \le \alpha \le 60° \end{array} \right) \tag{12}$$

Fig. 7. Reference vector as a combination of adjacent vectors at sector 1.

(a) Sector 1.
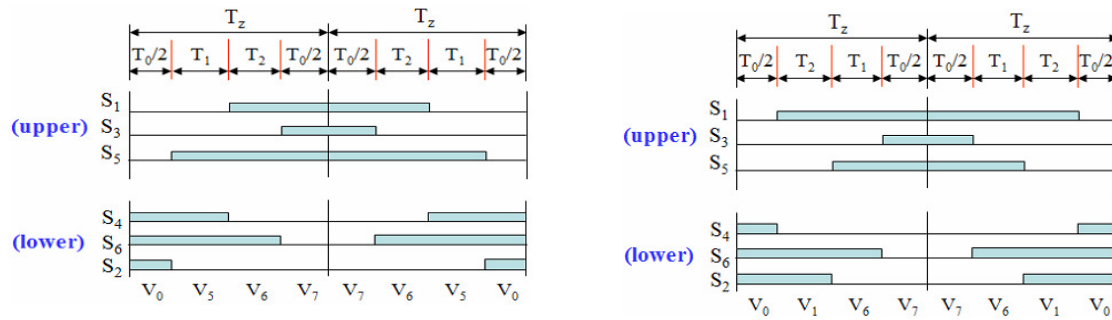

(b) Sector 2.

(c) Sector 3

(d) Sector 4.

(e) Sector 5.   (f) Sector 6.

Fig. 8 Space Vector PWM switching patterns at each sector.

Step 3: Determine the switching time of each transistor (S1 to S6):

Fig. 8. shows space vector PWM switching patterns at each sector. The switching time at each sector is summarized in Table 4, and it will be built in Simulink model to implement SVPWM.

Table 4. Switching Time Calculation at Each Sector

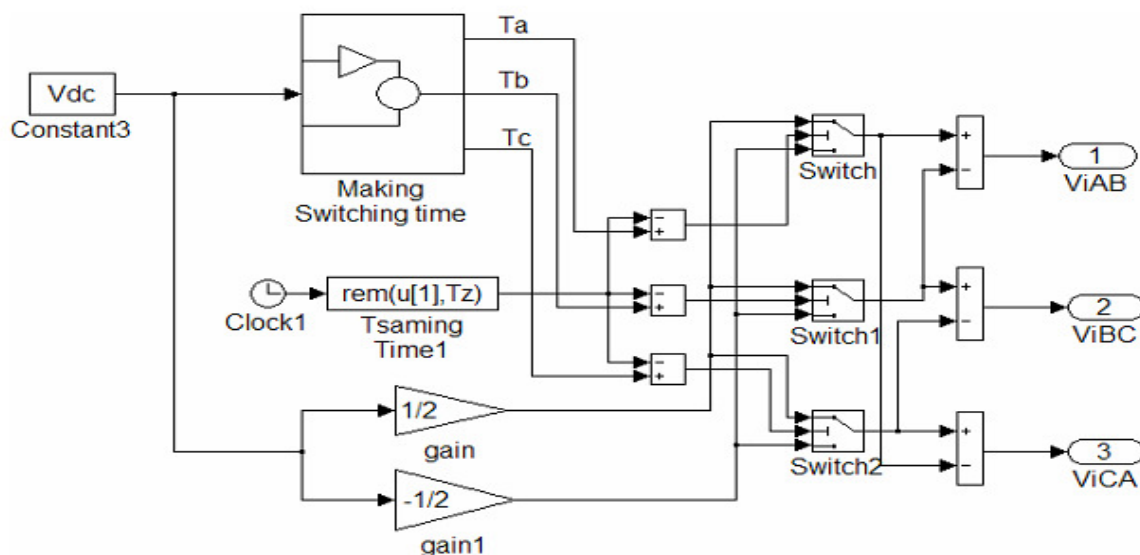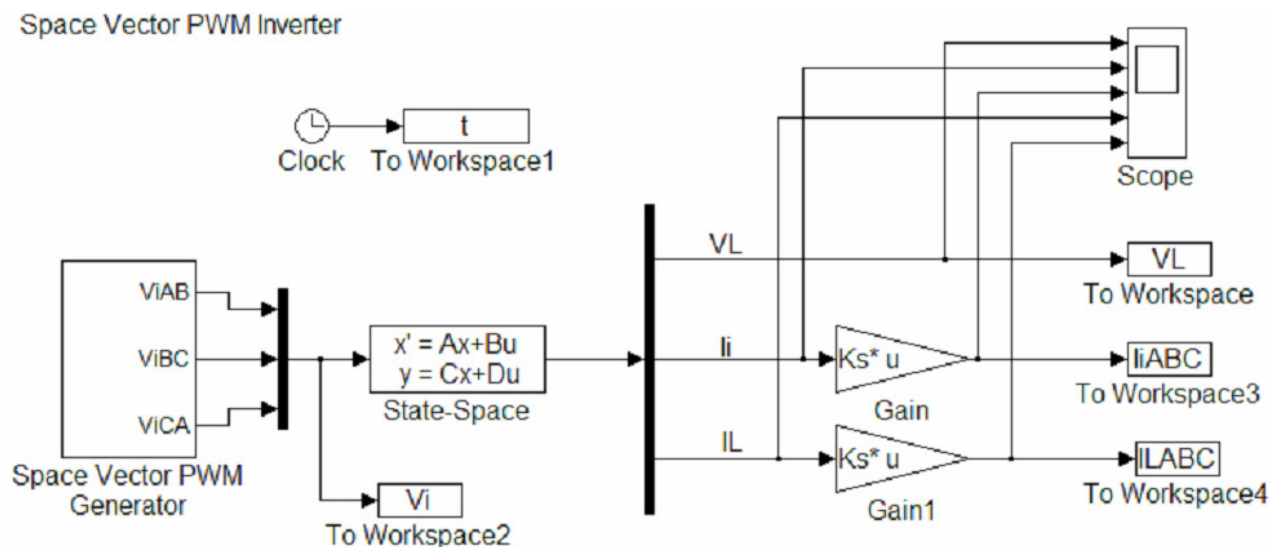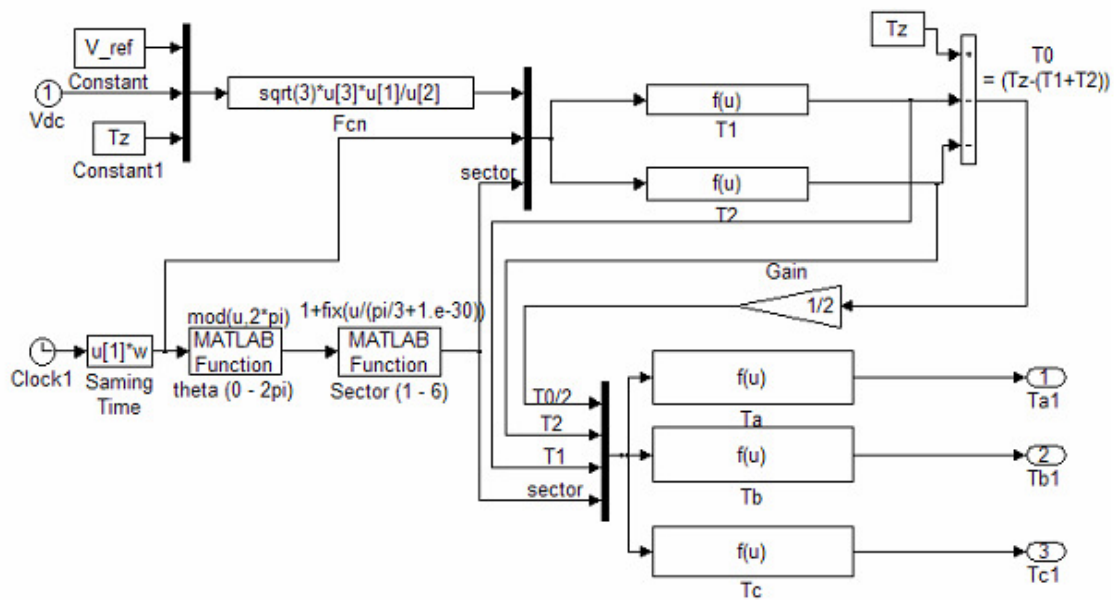| Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_2 + T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1 + T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_2 + T_0/2$ $S_6 = T_2 + T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_2 + T_0/2$ $S_2 = T_2 + T_0/2$

IV. SIMULINK MODELS and RESULTS

Following steps were used for obtaining simulink models and simulation results.

1). Initialize system parameters using Matlab

2). Build Simulink Model: Determine sector, Determine time duration T1, T2, T0, Determine the switching time (Ta, Tb, and Tc) of each transistor (S1 to S6) ,Generate the inverter output voltages (ViAB, ViBC, ViCA,) for control input (u) and Send data to Workspace

3). Plot simulation results using Matlab Simulink Model for Overall System is shown in Fig. 9. Subsystem Simulink Model for Space Vector PWM Generator is shown in Fig. 10. Subsystem Simulink Model for Making Switching Time is shown in Fig.11.
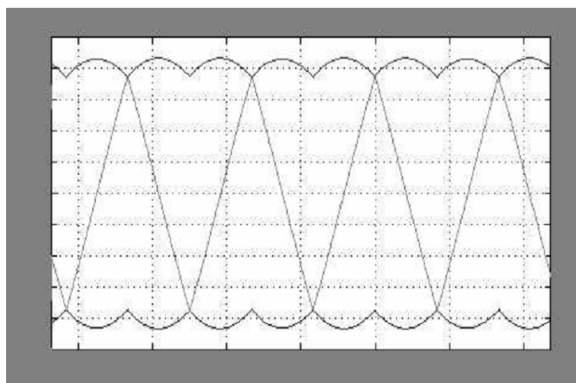
In Fig 12 duty cycles of two PWM switches are shown (taon, tbon,tcon).In Fig.13 sector numbers of the rotating reference voltage vector is given. The order of the sectors is the same as in case of a vector rotating in the direction of counterclockwise. In Fig.14, durations of the to boundary sector vectors are shown. In Fig.15, projection vectors of the reference voltage vector on (a b c) plane are shown in time domain. In the second simulation, a straightforward SVPWM algorithm is
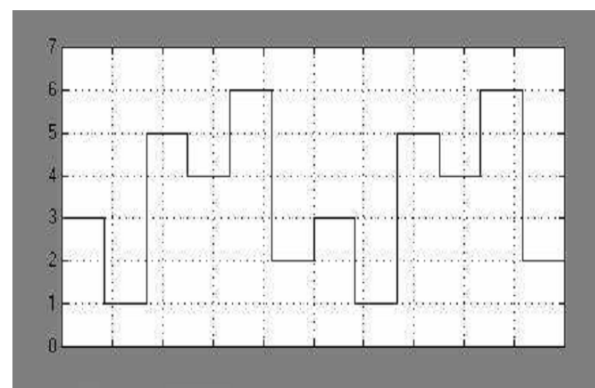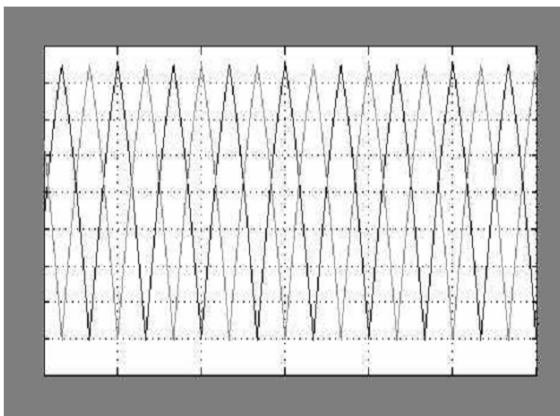
implemented ignoring optimal conditions for practical applications. In this simulation one can observe line-to-line voltages in the form of frequent pulses and the sampled signal (reference voltage) for varying modulation constants (see Fig.16 and 17).

Fig.9. Simulink Model for Overall System

Fig.10 Subsystem Simulink Model

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Fig. 11 Subsystem Simulink Model for Making Switching Time

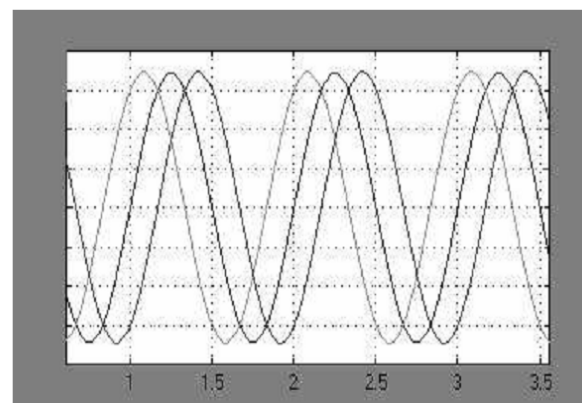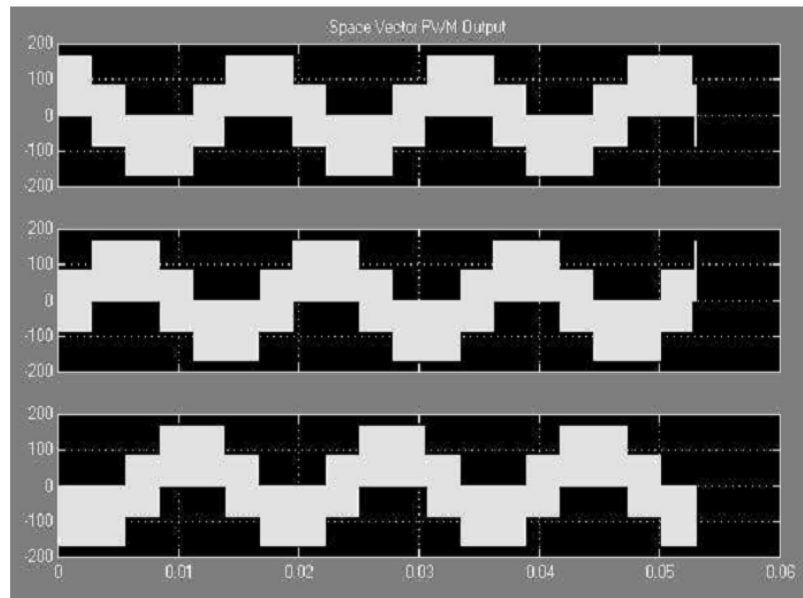**Fig.12** waveforms of duty cycles (taon, tbon,tcon)

Fig.13 Sector numbers of voltage vector

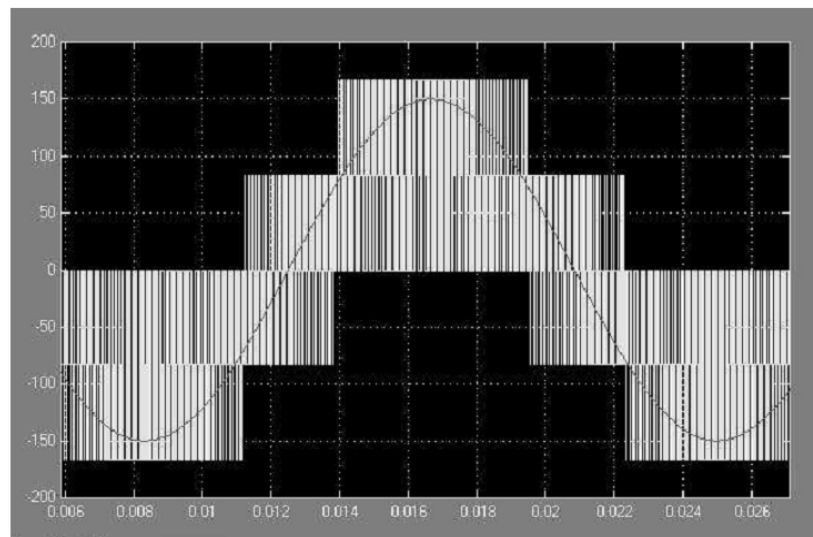**Fig.14** Duration of two sector boundary vectors (t1,t2)
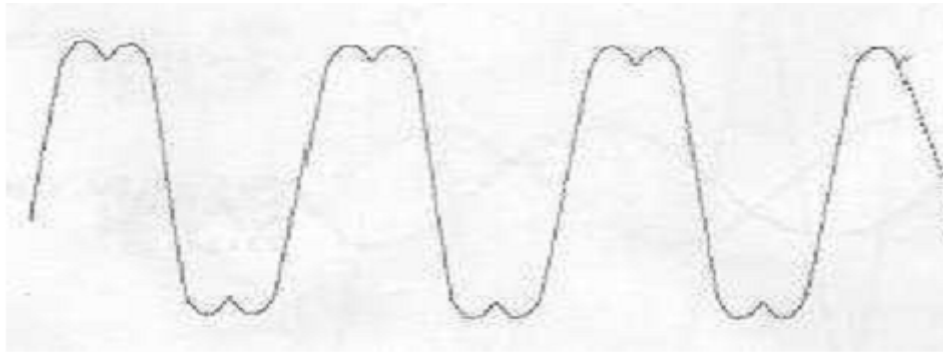

Fig15 The projections of the Va, Vb and Vc
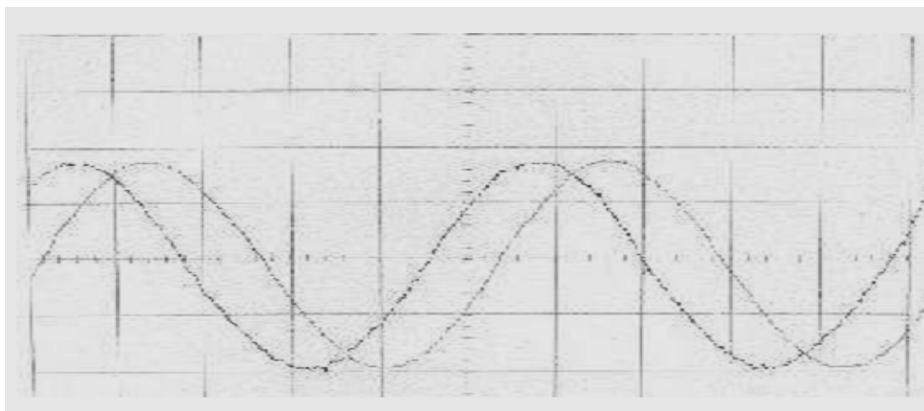
Fig.16 A typical line to line voltage output of SVPWM

Fig.17 SVPWM output with the signal sampled m=0.4)

V. EXPERIMENTAL RESULTS and CONCLUSION

The SVPWM algorithm is implemented here by DSP. The experimental outputs confirm the theoretical and simulation outputs. Given two reference voltage vectors associated with the reference currents and torque requirement SVPWM software parameters are observed and compared with the simulated ones. Fig.18 shows duty cycle of one of the PWM switches. The duty cycles is figured out by DAC outputs of the DSP processor.
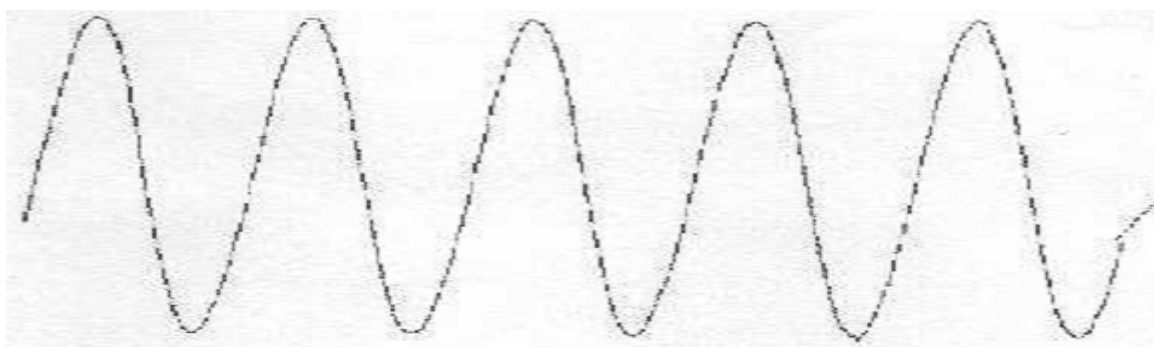
Fig.18- Duty cycle of PWM1

Fig.19 Projection vectors in abc plain (X,Y in time domain)

Fig.19 is the experimental result of projection vectors in abc plain . Typical phase current of an induction motor driven by SVPWM under heavy load conditions are shown in Fig 20.

Fig.20 Typical phase current of an induction motor driven by SVPWM under heavy load conditions.

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